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UNDERWATER SOUND REFERENCE LABORATORY REPORT

AN UNDERWATER SOUND ABSORBER
FOR
AN ANECHOIC TANK

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USRL REPORT NO. 31
15 September 1953

OFFICE OF NAVAL RESEARCH
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AN UNDERWATER SOUND ABSORBER
FOR
AN ANECHOIC TANK

by
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ABSTRACT

The work done at the USRL on the measurement of the sound-absorbing properties of various materials in water at hydrostatic pressures from 0 to 1000 psig in the frequency range 10 to 150 kc is summarized. Data are presented to show the improvement obtained by lining three different test vessels with the sound-absorbing material Insulcrete--a pine sawdust-Portland cement composition. Instructions are included for the construction of this material.

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AN UNDERWATER SOUND ABSORBER FOR AN ANECHOIC TANK

I. INTRODUCTION

A method to simulate free-field test conditions for underwater sound devices in an enclosed vessel was developed at the Naval Research Laboratory in 1942. This method, known as "pulsing", made possible the production testing of Sonar devices by many manufacturers located far from a suitable body of water and handicapped by rigorous winters.

Since that time, the pulsing technique has been fully described in the literature and widely used by those institutions engaged in research in underwater sound. The method, briefly described, consists of transmitting a short pulse of sound energy, opening an electronic gate, sampling the intensity of this pulse when it reaches the receiving hydrophone, and then closing the gate to avoid reflections from the ends and sidewalls of the water-filled vessel. If these reflections have not disappeared or been very highly attenuated before the level of the subsequent pulse is measured, inaccurate data results. To hasten the decay of this interfering energy, some type of sound-absorbing material must be installed in the tank.

The requirements of an ideal material are very exacting. It must have a reasonably high coefficient of absorption, be economical to construct, and easy to install. Its absorption characteristics must not change significantly with temperature, pressure, or age. The unavailability of any known material meeting the aforementioned requirements necessitated the establishment of a research program to determine what material would most nearly approach the requirements of the USRL.

The investigations, started five years ago, have suffered many unavoidable interruptions over the period of years. The experimental approach has generally been followed during those relatively brief intervals when time and equipment were available, and the theoretical side of the problem has not been fully analyzed. Inasmuch as a useable material (not ideal, but far superior to other known absorbers for the purpose) has been found, the urgency of the situation has been greatly relieved.

Although none of the three USRL projects under which these investigations were carried out has been brought to the full conclusion that might be desired, all are being closed for the present by this somewhat narrative account of USRL experience in evaluating the properties of absorptive materials in general, and searching for one particular material with superior properties.

II ABSORPTION MEASURING TECHNIQUE

The absorption coefficient was considered to be, and measured as, the reflection coefficient subtracted from unity when the sample neither transmitted nor scattered sound energy. The reflection coefficient was the ratio of reflected energy to normally incident energy.

Two test methods were used [1]*. The first was the wave cancellation method, in which a sound-receiving probe moved in proximity to a test sample and responds to the pressure differences caused by the interference of the direct sound pulse with the sound pulse reflected from the sample. The probe was motor driven at a constant speed away from and on a line normal to the midpoint of the test plate. The data so obtained were evaluated by comparison of the null depths produced when the test sample was in place with the null depths produced from a steel plate having a high reflection coefficient. From this method were obtained the coefficients α and β for determination of the complex acoustic impedance, $R+jX = \rho_0 c [\alpha + j\beta]$, where α is the coefficient of energy absorption and β is the phase shift coefficient--the distance of the first null from the sample surface with reference to the distance of a half wavelength in water. Solutions of the equation $R+jX = \rho_0 c [\alpha + j\beta]$ were readily obtained from graphical contour charts [2].

The second method varied the procedure of the first method (which used a fixed frequency and a moving probe) by fixing the probe at a predetermined distance in front of the test sample and transmitting pulses of sound energy while varying the frequency through the desired range. This method gave the reflection coefficient by measuring the pressure of the sound pulse as it passed the probe on its way to the plate and the pressure of the pulse reflected from the plate. The pulse was sufficiently short to prevent wave interference at the probe.

The latter method was chosen for the major portion of the investigation for a number of reasons. First, it was a much more rapid method of evaluating the samples over the frequency range 10 to 150 kc. Also, the reactive component of the complex acoustic impedance was considered unessential when examining widely different structures, although it would assume importance when slight deviations of a single sample structure were being studied. Second, a greater accuracy of measurement appeared obtainable under the adverse test conditions offered by the unlined tank. The first method showed an erratic distribution of nulls together with null depths varying randomly because of diffraction effects and high reverberation level. Furthermore, the first method was particularly unsuited for bulk absorption measurements, since some sound was then reflected from both the front and rear surface of the sample, increasing the erroneous null distribution and depth level. These two reflections could be separated by the second method by using a reasonably thick sample.

The first sample chosen for test was an 8x8x16-inch unreinforced concrete building block remaining after construction of the Pressure Laboratory building. This block was split in half and the two sides juxtaposed and backed by a 5/8-inch thick steel plate, making a test surface 16 inches square and preventing sound transmission.

*The numbers appearing in square brackets refer to the references at the end of the report.

By rotating this assembly through 180° in azimuth, a comparison of the reflection coefficient of the two sides was obtained. The reflection from the concrete was less than that obtained from the steel plate, showing some sound absorption by the material. A reliable quantitative measurement being impossible in the unlined tank, a decision was made to line the tank with this material with the hope of expediting transducer calibrations under hydrostatic pressure.

Building blocks were stacked in both ends and as high up the sides of the pressure tank (8 feet in diameter and 14 feet in length) as possible. The top of the tank remained unlined. Evaluation measurements made using a pulse repetition rate of 20 per second for comparison of the lined with the unlined tank showed a 30 db decrease in the reverberation level over the frequency range 10 to 150 kc after a delay of 49 milliseconds, which coincided with the transmission of the succeeding pulse. This reduction, which made the tank available for acoustic measurements, was reported in a paper before the members of the Acoustical Society of America [3].

III. MEASUREMENT LIMITATIONS

At the very outset of the absorption-measuring program, acoustical, electrical, and physical limitations were encountered. Many of these were caused by the necessity of testing in a closed vessel rather than a free field. One major limitation was the inability of transducers and probe hydrophones to withstand the hydrostatic pressure to which they were necessarily subject. The mortality rate of probes was extremely high when subjected to 300 pounds per square inch (gage).

Rather than to digress at this point with a discussion and enumeration of a few of the obvious limiting factors, this discussion is presented in Appendix 1.

IV. MEASUREMENT OF ABSORBERS

At the start of this program, very little practical information was obtainable about underwater sound-absorbing materials. Some were in use, but data were unavailable for evaluating their worth to the USRI needs. The existing absorbers were apparently designed not only for a very narrow frequency band, but without regard to large changes in temperature and pressure. The development of a sound-absorbing material appears to have been an unpopular task in the field of underwater sound research.

The most logical approach to the development of a sound absorber seemed to be the testing of existing absorbers and available porous structures. A list of some of the materials which were examined follows, with only a limited discussion when not considered pertinent to this report.

(1) Baffles -- The baffles were of various shapes and were used in domes to screen echo-ranging transducers from propeller noise and to reduce specular reflection when the transducer was trained aft. The usual internal construction consisted of twenty layers of fine mesh screen separated by expanded metal and operated in a bath of castor oil. They showed an absorption coefficient of 0.5 at their approximate

operating frequency of 24 kc. At high frequencies, the reflection from the flat, expanded-metal separators proved to be considerable, masking further evidence of increased absorption.

(2) Alberich - Alberich was the German-invented sound absorber used as a non-reflecting coating for submarines during the latter part of the war. It consisted of resonant air pockets enclosed by rubber having a high dissipation factor. The test sample was obtained from the conning tower of a captured U-boat about three years prior to the time of testing, and was suspected to have deteriorated greatly with age. (The effect of age was confirmed recently in a conference with Dr. E. Meyer, the inventor of this material and Fafnir). Any absorption shown was within the limits of measurement accuracy.

(3) Fafnir - To speed pulse decay time, the German underwater sound engineers lined their sound test vessels with wooden plates on which were mounted parallel rows of low-grade synthetic rubber teeth. This array appeared similar to mythological dragon teeth and so was named Fafnir. A waterproofed wood-tooth replica was constructed. It produced absorption losses identical to those obtained with the Fafnir structure, making the rubber material appear unimportant for further study. An analysis of the absorption characteristics of this material itself, eliminating the effect of the geometrical arrangement, would have required a flat sheet, which was unobtainable.

(4) J2024 - This number was the official designation of a sound-absorbing rubber coating material developed by Harvard and MIT scientists under government contract. The absorption coefficient of a badly weathered sample varied from 0.7 at the lower frequencies to 0.3 at the higher frequencies.

(5) Concrete - A large slab of concrete, constructed of material identical to the building blocks lining the tank, showed an absorption coefficient of 0.5 for sound at normal incidence. This appeared to be a promising figure, and many experiments were conducted to determine the possibility of obtaining greater absorption. A theoretical consideration of the mechanism of absorption led to the belief that an increase in viscosity of the medium in the voids of the porous material would obtain an increase in the absorption coefficient of the material. An open-face steel container was constructed around a concrete sample and the face covered with ρ c rubber. This assembly was evacuated and then filled with castor oil. Although the data were not absolutely conclusive, a liberal interpretation made possible the conclusion that the absorption coefficient had been further increased by 20%.

Various configurations of the test sample face were constructed. Conical protuberances (2-inch base, 3-inch height) to introduce multiple reflection were tried, but were quickly discarded and replaced with conical holes (2-inch base, 3-inch depth) so as to provide greater structural strength. This assembly, except for a narrow band of frequencies between 60 and 90 kc, showed an absorption coefficient in excess of 0.9 over the frequency range 10 to 150 kc. (This coefficient included energy which was scattered.) This level of absorption remained unchanged at hydrostatic pressures up to 300 psi. Cylindrical holes (1/2-inch diameter, 3-inch depth) drilled in the face of the absorbing sample gave results similar to those obtained by the use of the conical holes.

Haydite and cinder block were also tested, both showing slightly higher absorption than the flat concrete slab.

(6) Wood - The recollection of data taken years prior to these tests and using the first model XCG portable pulsing equipment led to further examination of wood. The absorption coefficient of pine wood had been found to be 0.5 over the limited frequency range 20 to 40 kc. This discovery occurred incidentally to the testing of mud bottom samples from the Rappahannock River--a location where fathometer echoes were not detectable, as if the ship were passing over a bottomless cavern. This absorption by wood was not surprising after considering that it was a porous material and had nearly the same characteristic acoustic resistance as water--the velocity being higher, but the density lower. Measurements made at this laboratory confirmed former findings, with the absorption remaining at a constant level over the expanded frequency range.

One of the steel test plates was coated liberally with Vulcalock cement on which was sprinkled pine sawdust. When the first layer was dry, another was applied. The treatment was repeated many times until a thick layer of embedded sawdust was obtained. The results were disappointing, showing the same absorption as the solid pine wood.

(7) Insulcrete - A conference with the Florida engineering consultant for the cement trade about the possibility of substituting crushed ice for water to greatly increase the porosity of concrete led to some discussion of a building material called Insulcrete.

This product is manufactured locally and used as building insulation. It consists of a mixture of pine sawdust, Portland cement, and decorative pebbles, and is internally reinforced with heavy wires. The small stones and the wires were omitted in the construction of the sound-absorbing samples, and the spelling of the name was changed to "Insulcrete" to denote the difference. Directions for making Insulcrete are given in Appendix 2.

The very first tests of this material showed it to be far superior to any other material tested. Its coefficient of absorption ranged from 0.90 at 10 kc to 0.99 at 100 kc, and, at frequencies between 1.0 and 1.5 megacycles, the sound reflected from the sample face amounted to only one part in ten thousand. The above figures appeared unchanged with application of hydrostatic pressures to 300 psig.

The density of the material is 1.1 g/cc when dry, and increases to 1.4 g/cc when wet. The average measured value of sound velocity is 1.9×10^5 cm/sec. The material approaches an ideal, as it can be graded in density and porosity by an acid etch, by the use of additional water when mixing, or by tamping to various degrees when forming. It readily adapts itself to tank lining, as it can be preformed or hand-sawed, and nailed or screwed in place. When used in a test tank, it causes the water to become highly alkaline--especially undesirable when testing aluminum-cased instruments. The use of acid for neutralization or the continuous addition of fresh water has been suggested for those tanks which have been lined with this material.

The transformation of sound energy to heat in the absorption process was readily made visible by Schlieren photography [4]. Figs. 1 and 2 show the heat developed by a small Insulcrete block when subject to high-frequency sound for various lengths of time [5]. Fig. 1 (reproduced from Polaroid Land Camera prints) shows the

sample before and after having been exposed to ultrasonics at a frequency of 600 kc for 20 seconds by the sound source shown at the extreme right of each picture. Sound power was halted just prior to the exposure of the photograph on the right so as not to mask the heating effect, which shows up as a light area.

Fig. 2 shows two samples before and after exposure to sound for 30 seconds at a frequency of 1 mc. At the extreme right of the picture is part of the face of the barium titanate projector. To the left and in close proximity to the projector face is a baffle plate to retard circulation ("sonic wind") which would tend to dissipate the heat from the immediate vicinity of the sound-absorbing sample. The baffle was made of aluminum foil one mil thick and supported by a corprene framework. To the right of the mid point of the picture was placed a rectangular piece of tan ρ c rubber one quarter inch thick. The Insulcrete sample was located to the left of center. Both samples were fitted tightly in the plate glass tank to prevent leakage of sound around the edge of the material. The lesser heat developed by this rubber may be compared to that developed by the Insulcrete block, allowing some estimate of their relative absorbing ability, although the sound intensity incident on the Insulcrete was only 70% of that incident on the rubber due to the attenuation through the latter. Tan ρ c rubber was chosen for comparison after study of a journal article [6] which said: "At a frequency of 3.35 megacycles a $\frac{1}{2}$ inch thick liner [tan ρ c rubber] provides results which are close to optimum, yielding a reflection coefficient of about -30 db up to an angle of incidence of about 60°". Although this frequency is three times higher than the frequency used for Fig. 2, considerable absorption could be expected at one megacycle, even for unidirectional transmission.

V. SMALL TEST TANKS

A small, rectangular tank, borrowed from an inactive Schlieren exhibit, provided the first experimental set-up for determination of the practical value of Insulcrete for c-w measurements. The tank was far too small to be of much value for underwater tests, but proved sufficiently large to obtain information regarding the practicality of a continuing investigation.

Insulcrete wedges one foot in length were stacked in the ends of the tank, and discarded sample test plates of the same material were placed on the top, bottom, and sides to provide a central baffle. After the addition of the absorbing material, little space remained for the positioning of transducers; nevertheless, the limited information gained substantiated the belief that c-w testing over a limited frequency band would be practicable in a suitably dimensioned tank—a vessel where sidewall reflections would be more highly attenuated by a specially designed central baffle. The transmitting or receiving response level of transducers could be established with an error no greater than ± 1 db over the frequency range 20 to 150 kc. Any variation in impedance measurements caused by the lack of free field conditions was within the limits of measurement accuracy. It was only the directivity patterns that could not be plotted accurately, due to the aforementioned interfering reflections from the inadequate central baffling. The wedge array at the ends of the tank had an absorption coefficient of 0.99, in the frequency band 40 to 80 kc, declining at lower frequencies and increasing at higher.



Fig. 1. Heating due to absorption of sound by Insulcrete

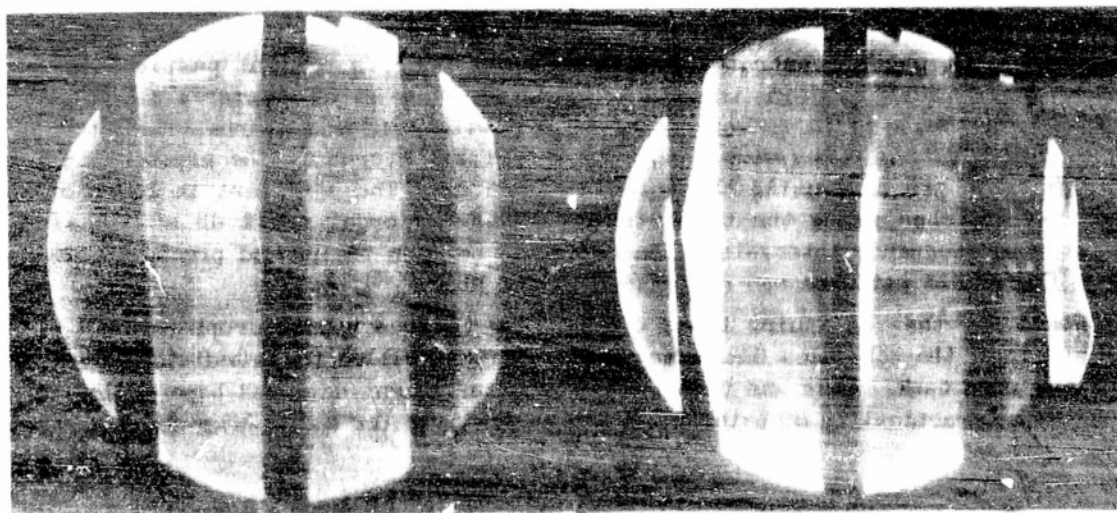


Fig. 2. Heating due to absorption of sound by 1/2 rubber and Insulcrete

Some difficulty was experienced at the higher frequencies by standing waves between the faces of the two transducers because of their inadequate separation. A solution to this problem was obtained by using externally connected lagging inductors to properly phase rectangular segments of the square projector crystal mosaic and rotate the directivity pattern 10 degrees from the normal. This made it possible to operate the transducer with its face in a plane not parallel to the face of the second instrument [7]. Another solution would have been an increased test distance, but this was unobtainable with the small tank.

Free-field testing facilities being readily available at this laboratory, small tank investigation was discontinued in favor of projects carrying higher priority, however, interest in small-tank testing was renewed when an answer could not be given to a problem posed by a group of acoustical engineers associated with a major manufacturing company. The question was, "Can an inexpensive tank set-up be constructed which will permit satisfactory production testing of transducers over the frequency range 50 to 70 kc, using c-w rather than a pulsing technique?" The tests were to include transmitting and receiving response, impedance, and directivity patterns. The accurate determination of directivity patterns presented the only unsolved problem, but it appeared increasingly difficult of solution upon learning that the instruments to be tested were being built with the most advanced design of lobe suppression, the minor lobes being down at least 30 db. The solution to the problem lay in the design of a second wood tank having an adequate size for acoustical tests, but still requiring as little floor space as possible. With these limitations in mind, an 8'x4-foot plywood tank was constructed and completely lined with wedges, allowing a testing volume 6x2x2 feet. This tank is shown in Fig. 3. The wedges were one foot in length, had base dimensions of six inches cube, and were arrayed with adjacent dihedrals at right angles.

All effort was concentrated on directivity patterns of that particular model transducer. Polar patterns were made from 50 to 70 kc at 5-kc intervals in the tank using c-w. These patterns were then compared with similar patterns made with free-field conditions. They were also compared with patterns in the pressure tank at atmospheric pressure using the pulsing technique. The agreement in level of the secondary lobes among the three tests was of the order of ± 1 db at the aforementioned frequency intervals. The agreement between the pulsed pressure tank and the free-field patterns was no better than ± 1 db.

Plans for the continuing tests of the many various type hydrophones had to be shelved, as the scheduled UERL move to new quarters called for immediate disassembly of the wood tank. This was unfortunate, but sufficient data had been collected to prove the practicality of using Insulcrete as a liner for small water-filled tanks.

VI. PRESSURE TANK

The experience gained in the construction of the two small tanks proved invaluable when the new 1000-psi pressure tank was to be readied for acoustic tests.

The new pressure tank, shown in Fig. 4, is 25 feet in length and 100 inches in diameter, with steel sidewalls 4 inches thick. The temperature can be controlled from the boiling point of water down to 2° C. The rate of pressure increase or

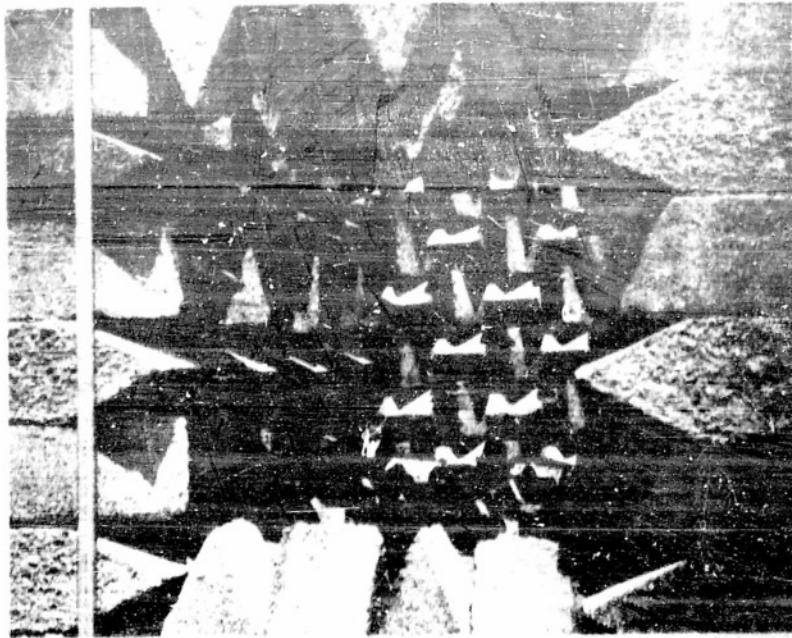


Fig. 3. Insulcrete wedges in small test tank

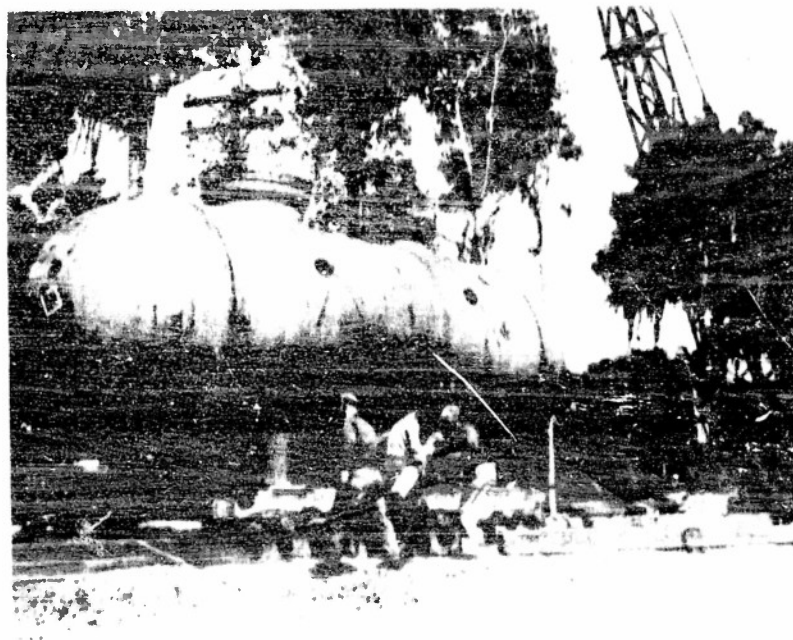


Fig. 4. USRL 1000-psi pressure vessel

decrease can be varied from 5 to 35 pounds per minute. Topside ports permit the rigging of transducers about 8 1/2 feet from the concave ends of the tank, making the acoustic test distance 8 feet.

Two of the projectors used for evaluating the tank had crystal arrays 4 inches square. Two other projectors had a much lower directivity index, as their active element was only one inch square. Two small omnidirectional probes were used as the receiving hydrophones. This duplication of instrumentation was considered necessary in view of former experiences with the breakdown of transducers subject to continued hydrostatic pressure cycling.

The data were recorded in two ways. First, the oscilloscope screen was photographed with pulsed transmission and with an ungated, or open, receiving system, from 10 to 150 kc in 5-kc increments for visual comparison of the over-all reflection reduction obtained by each addition of sound-absorbing material. Photographs were made with pulse repetition rates of 30 and 60 per second, but only those made at the latter figure are presented in this report. All frequency settings for comparable pictures at progressive stages of lining completion were reproduced exactly; that is, a Berkeley Universal Counter was employed to monitor the standard oscillator setting. By the second method, additional permanent data were obtained on a linear recorder from 10 to 150 kc by sampling the signal level at discrete time intervals after the pulse transmission. This method gave more nearly accurate quantitative data, providing a smooth rather than stepped plot throughout the frequency band. In both cases, all measurements of reflection and reverberation levels were compared to the level of the direct received signal in order to compensate for random changes in projector output or receiving sensitivity which sometimes had occurred when test periods were extended over a long period of time.

Fig. 5 is an end view of the inside of the tank after the wedge-supporting framework had been bolted to available lugs. It was with these frames in each end that the first measurements were made on the tank. The frame was so constructed that the wedges, varying in length from 4.5 to 5 feet, were self-supporting when stacked in place. Small wedges one foot long were stacked around the framework so as to completely fill the void annular area as shown in Fig. 6. The central baffle is composed of eight to ten circumferential rows of 1-foot long Insulcrete wedges with their dihedrals arrayed parallel to the axis of symmetry of the tank. The bottom wedges are self-supporting, being stacked to a point midway up the sides of the tank. The upper half of the block assembly is supported by many equally spaced longitudinal rods which fit specially molded indentations in the tapered wedge bases. A picture of the central baffle with the end wedges in the background is shown in Fig. 7.

Prior to presentation of the "before and after" oscilloscope pictures, a brief explanation of their interpretation seems to be in order. Although the repetitive pulses shown in Fig. 8 probably will be self-explanatory to those practiced in the use of the pulsing technique, they are undoubtedly unintelligible to initiates.

The first pulse from the left in Fig. 8 is the monitored electrical transmitted signal which is fed to the projector. The second pulse is the signal received by the hydrophone in the most direct path. In between these two pulses lies a region which contains only energy from a preceding pulse, and it is at this point where the signal level was sampled to determine if sufficient attenuation of the preceding

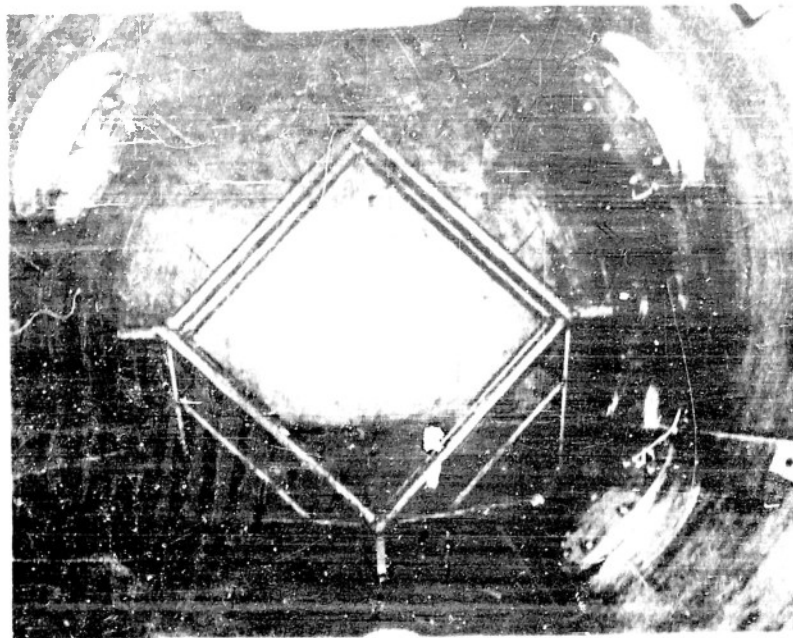


Fig. 5. Framework for supporting Insulcrete wedges in end of USRL pressure vessel

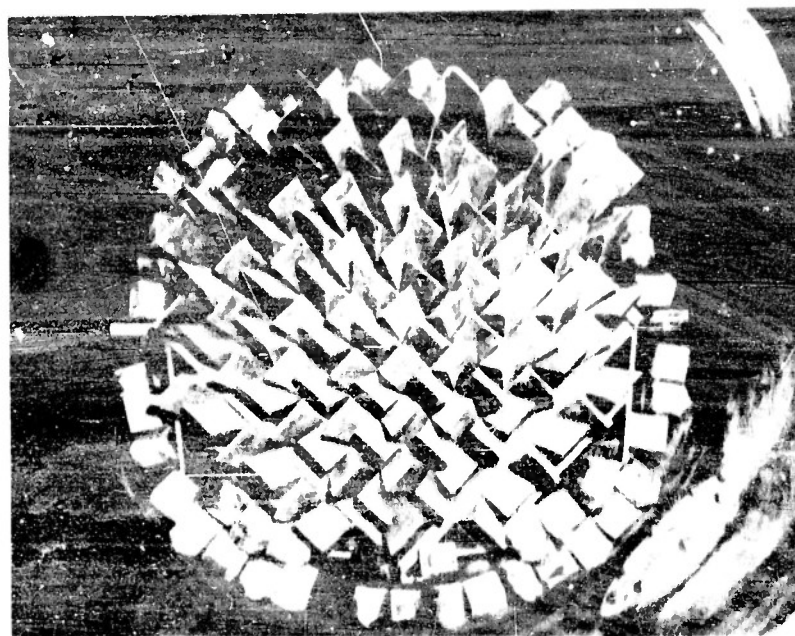


Fig. 6. Insulcrete wedges installed in end of USRL pressure vessel

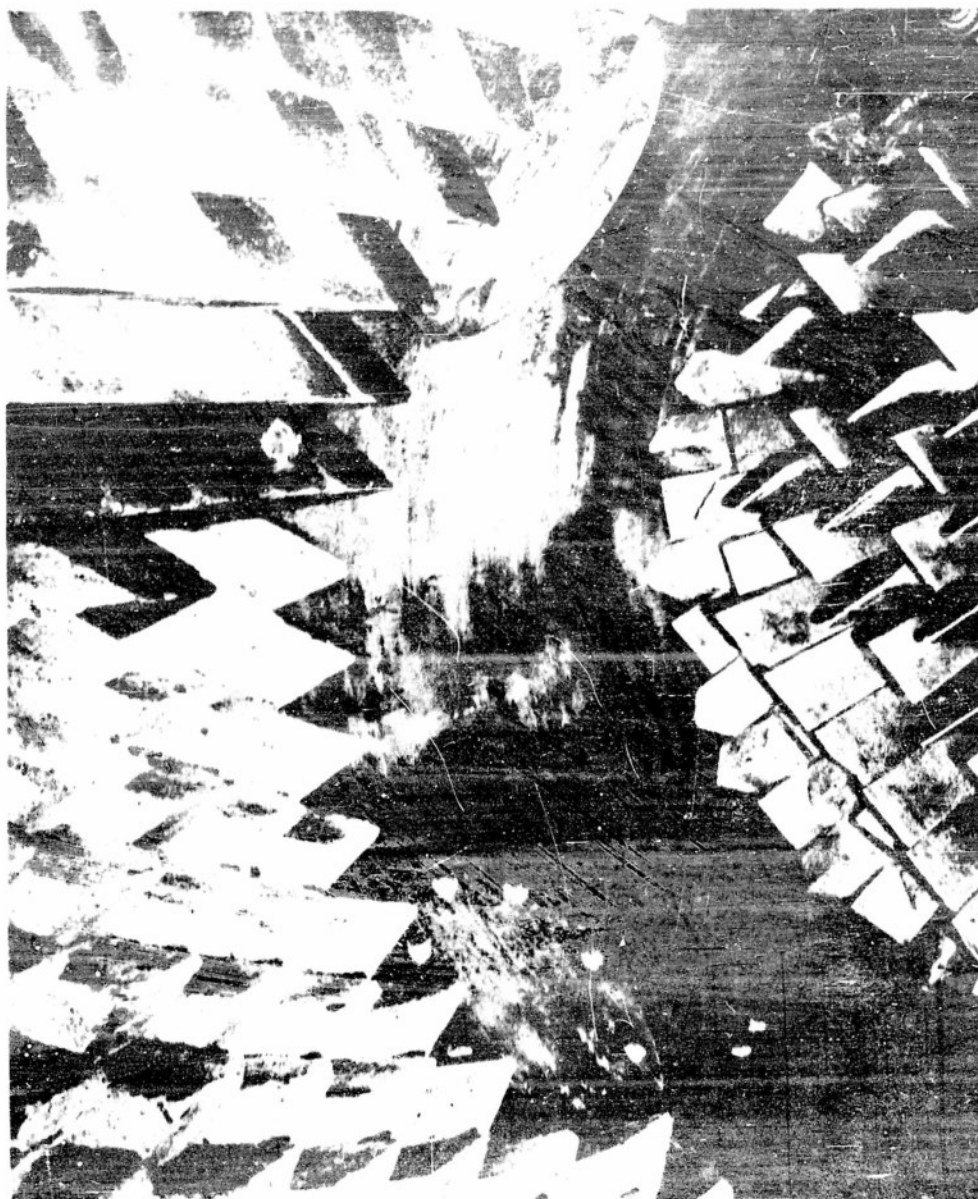
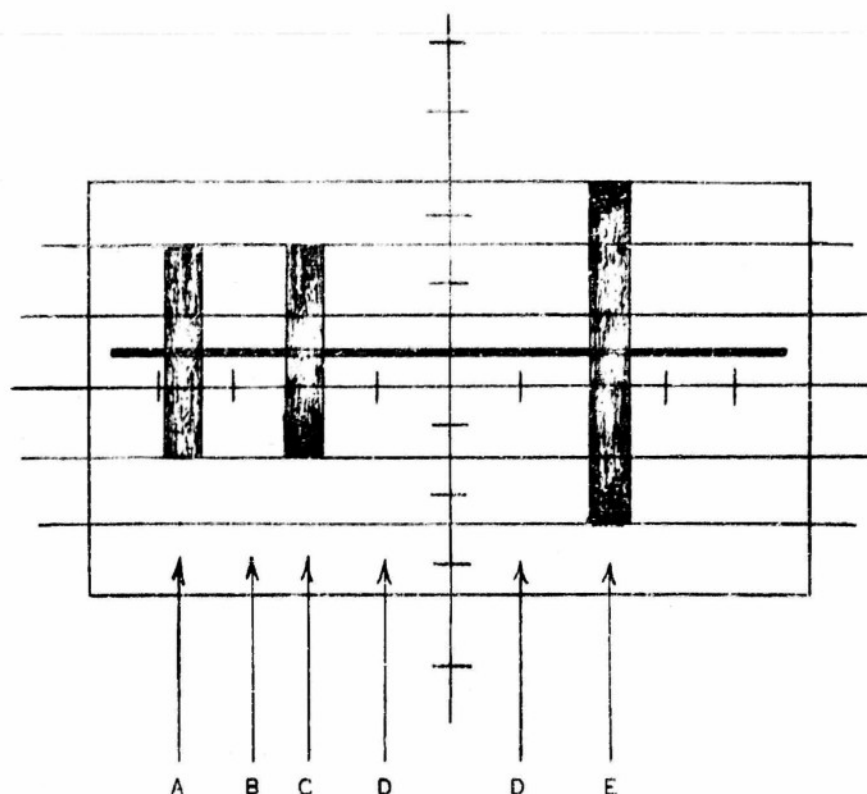


Fig. 7. Insulcrete baffle in center and end of USRL pressure vessel



- A. MONITORED TRANSMITTED PULSE
- B. ENERGY FROM PRECEDING PULSE
- C. DIRECT RECEIVED PULSE
- D. REFLECTION FROM SIDEWALLS PLUS ENERGY FROM PRECEDING PULSE
- E. REFLECTION FROM TANK END

Fig 8. Oscilloscope presentation of pulse sequence

pulse had been obtained so as not to influence the level of the pulse to be measured. This interference may be thought of as reverberation level. Following the second pulse are reflections from the sidewalls of the tank taking a multitude of angular paths to finally reach the receiving hydrophone. A pulse has been photographed after having been reflected from the sidewalls more than ten times before it reached the probe. The reflections may be much higher than the direct signal, particularly in a tube-like vessel where symmetry causes addition of the reflections. The pulse to the right of the figure is the reflection from the concave end of the tank. Its high level is due to the probe being positioned near the focal point of the highly reflecting concavity. The level of this reflection could not be recorded accurately due to the arrival of reflections from the sidewalls at the same time.

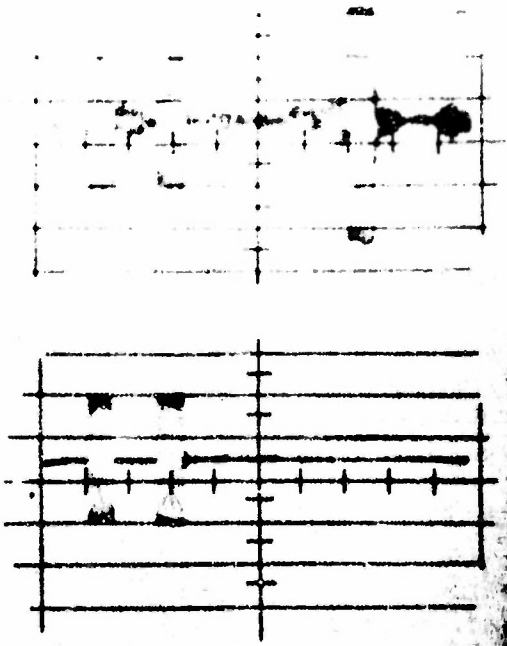


Fig. 9. Oscillograms of pulses in USRL pressure vessel, before and after lining with Insulcrete

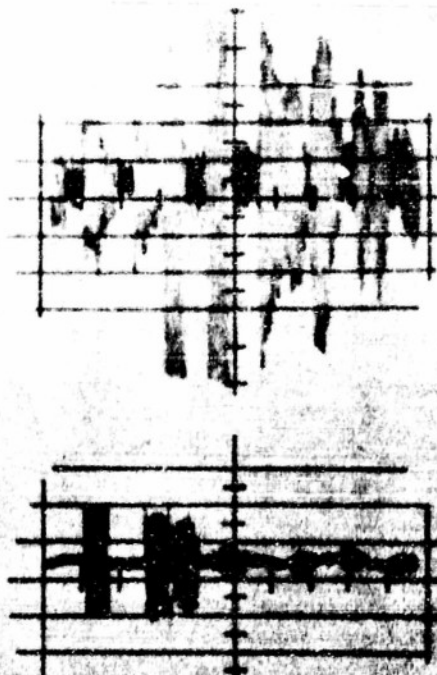


Fig. 10. Oscillograms of pulser in USRL pressure vessel, with one end lined with Insulcrete and with full Insulcrete lining

The oscillograph base line was purposely placed above the center line so as not to mask the short vertical markers on the graticule abscissa which were used as a time or distance scale. The time between the markers was one millisecond, equal to a sound path of approximately 5 feet in the tank.

At the top of Fig. 9 is a photograph of the reflections in the bare tank at a frequency of 60,074 cycles per second. This photograph is so similar to the drawing in Fig. 8 that little further explanation is necessary. The level of the area in Fig. 9 between the direct received pulse and pulse reflected from the tank end was due to the energy from the preceding pulse rather than from sidewall reflections. At this frequency the directivity index of the projector was sufficiently high to transmit the sound beam along the axis of the tank without contacting the sidewalls at the necessary angle for reflection to the probe hydrophone. The bottom photograph in Fig. 9 is to be compared with the upper picture. All test conditions have been maintained except for the addition of the Insulcrete wedges. There remained little trace of interfering reflections, and measurements made with a continuous wave had the same accuracy as those made using a pulsing technique.

The two photographs in Fig. 10 were made at a frequency of 10,000 cycles per second. The upper reproduction was not made with the tank bare, but with wedges installed in the end of the tank nearer the hydrophone. An oscillogram made at this frequency with the tank bare showed the directly received signal to be entirely masked by the sound from the preceding pulse. A slight misadjustment of the oscilloscope controls unfortunately displaced all reflections toward the left. This placed the third marker from the left at the end of the directly received pulse

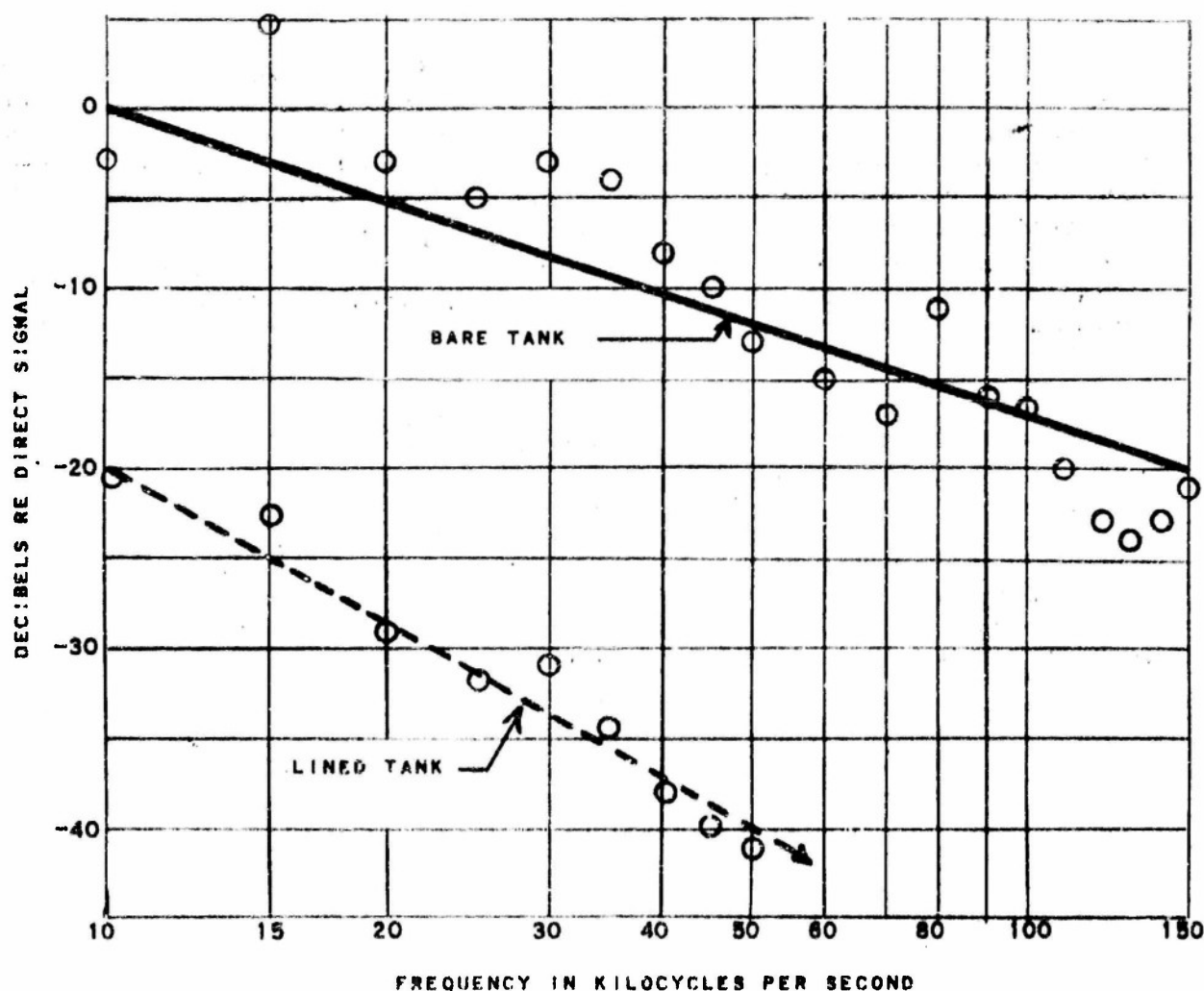


Fig. 11. Level of reverberation for bare and lined tank

rather than in its center as was shown in all other pictures. Sidewall reflections are shown to be of sufficient intensity to displace the pulse peaks from the oscillograph face. It was necessary to operate at this gain in order to maintain a uniform 3-cm height of the received pulse.

The lower photograph again pictures the improvement obtained by the addition of the wedge lining. At this frequency the levels of the reflections are too high for continuous-wave testing. An improvement of this condition could be obtained by the use of longer wedges for the central baffle or by the use of either more directional transmitting or receiving transducers.

Fig. 11 is a graph of the decrease in reverberation level associated with the installation of the sound-absorbing wedges. These data were obtained from linear recorder traces of the signal level measured between the transmitted and received pulses, or at point B in Fig. 8, and then compared with the level of the direct

received pulse. Sound levels more than 40 db below the direct signal could not be recorded--the low receiving response of the probe hydrophone made high gain amplification necessary, causing the inherent noise level of the electronic measuring system to mask the reverberation. A specially designed receiving system could have been assembled for the low-level measurements, but the data obtained would have been of academic rather than practical value where the interfering signal level was lower than 40 db. The reverberation level could have been lowered to an immeasurable quantity by decreasing the pulse-repetition rate to 20 per second.

Continued observation over a period of some months has indicated no change in the absorption coefficient of the wedges at hydrostatic pressures to 1000 psig, or at temperatures as low as 3° C.

VII. CONCLUSION

Insulcrete in its present state of development has been recommended as a sound-absorbing lining for small tanks, and is in current use in that capacity. An intensified effort to improve the absorption of this material should be made. The optimal aggregate is not necessarily pine sawdust, nor Portland cement the perfect cohesive agent. There remain literally thousands of tests that can be made, with possibly hundreds of improvements to evolve.

Appendix i

ACOUSTICAL, ELECTRICAL, AND PHYSICAL LIMITATIONS ON MEASUREMENTS

Some of the acoustical, electrical, and physical limitations encountered during the investigations with which this report is concerned are discussed below.

Pulse Length

The minimal length of the transmitted pulse had to contain at least three cycles so that the level of the received pulse could be automatically recorded by the sampling of at least two cycles. A frequency of 10 kc appeared to be the lower limit of the transducers, making a pulse length of at least 300 microseconds compulsory. This was a pulsed train of underwater sound waves about one and a half feet in length, which limited the probe to distances from the test plate greater than half the aforementioned length, if interference between the direct and reflected waves was to be avoided. The pulse length maximum was limited by interference from the sound waves reflected from the sides, top, and bottom of the tank, and by the test sample size.

Sample Size

The minimal size of the test plate was determined by the necessity of measuring the level of the reflected pulse prior to the setting up of diffraction phenomena. Fig. 12 compares the measured levels of the reflection from two different sized steel plates with the theoretical value for an infinite plate over the frequency range of 10 to 100 kc. The solid curve was the level of the reflection from a steel plate 14x14x5/8 inches. It shows large irregularities throughout the frequency range when measured with the probe hydrophone placed 25 cm in front of the plate and using a pulse length of approximately 300 microseconds. The dotted curve was obtained under the same test conditions, except the size of the test plate was increased to 24 inches on a side. Nearly complete absence of diffraction effect was shown by the close agreement of this curve with the theoretical, or 0-db level. The size of the ports (24-inch diameter) in the test tank made examination of plates larger than 24 inches infeasible.

Test Distance

The minimal test distance from the sound source to the test plate was limited by the desire to cover the plate with an approximately plane wave. The maximal separation obtainable was determined partly by the limiting length of the tank and partly by the necessary difference in sound path between the directly received signal and the signal reflected from the sidewalls of the vessel. The convenient test distance of 6 feet was chosen for most of the investigation and appeared to be sufficiently great so that spherical wave corrections were considered unnecessary.

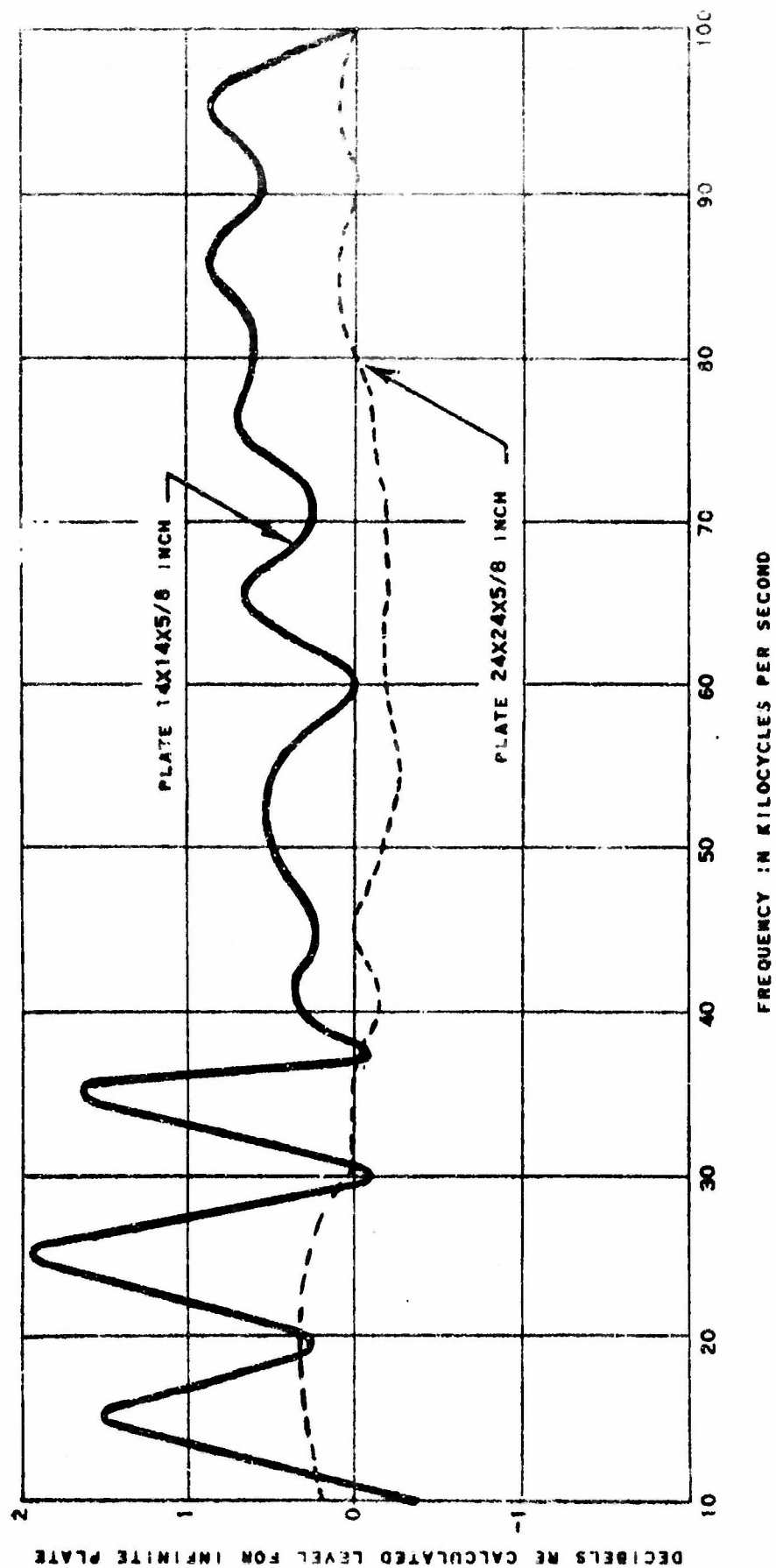


Fig. 12. Reflection level of two sizes of steel plates compared to theoretical level from infinite plate

Probe Hydrophone Directivity

The receiving response of the two faces of the sound-sensitive probe always was found to differ in level by at least one decibel over the frequency range 10 to 150 kc. This statement applies to more than a dozen probes used during the project and, although trivial, was annoying. The variation in level made it impossible to compare directly the reflection from the steel plate with that obtained from the absorbing material placed in front of the plate; a varying correction for the probe had to be applied throughout the frequency range.

Standard Reflector

Calculation of the reflection coefficients of varying thicknesses of steel plates showed 5/8 inches to be a satisfactory thickness in water over the desired frequency band. An air-filled volume would have been superior, but construction of a compensated air enclosure for high hydrostatic pressures did not appear sufficiently essential to warrant the outlay of the required labor and material. The steel plate was considered to be a perfect reflector for a comparison measurement to obtain absorption coefficients. Numerous measurements showed the steel plate to be nearly equal to an air-backed reflector. An inverse square law distance correction was applied to all reflection measurements because of the relative proximity of the sound source.

A short series of measurements was made to determine the accuracy with which transmission and reflection coefficients of 24-inch-square plates could be measured in the frequency range 10 to 150 kc. A 1/8-inch brass plate and a 3/32-inch steel plate were chosen. A short pulse was used to measure the transmitted and reflected energies before the formation of the plate diffraction pattern. The direct and reflected energies were measured with a bidirectional probe at a distance of 19 cm in front of the plate. The transmitted energy was measured with the probe mounted one centimeter behind the plate.

Corrections for test distance variation of the probe with changing location were calculated theoretically and verified experimentally. Corrections were also applied for the response difference of the two faces of the probe throughout the frequency range.

When experimental data were plotted against theoretical curves of reflection and transmission for infinite plates having similar thickness and acoustic impedance, the experimental results invariably proved to be low.

The final analysis of the data to determine the over-all accuracy was performed by summing up the fractional reflected and transmitted energies and comparing the sum to unity. The final curve showed the measurements to be low by an average of one decibel through the entire frequency range (10 to 150 kc). This inaccuracy could have been caused by the inability to prevent the thin plates from warping slightly and presenting an irregular reflecting surface to the receiving probe.

Transducer Q

Transducers having a high Q had to be rejected for all measurements. Sharply resonant transducers could not be used with the short pulse because sufficient time for build-up of a steady-state signal was not available.

Harmonics

Three factors could have contributed to the introduction of high level second and third harmonics into the measured signal level. The first source of trouble was electronic. Oscillators, never being perfect, accentuated the harmonics with increasing age, changing slowly over a long period of time. At times, the harmonic content increased suddenly and without warning. A constant check of oscillator and amplifier waveform had to be maintained. A second contributing factor was acoustical in nature. Transducers which had an ascending response level with increasing frequency tended to accentuate or amplify the harmonics. Even though the harmonic output of the oscillator was 40 db below the fundamental, a steep rising response curve would bring the level of the harmonics up to that of the fundamental. The third factor contributing to the introduction of harmonics was the nonlinearity of projectors when driven at high power levels.

These harmonics had little effect on measuring the reflection from the steel plates, where the level of the reflection was practically constant throughout the frequency range, but was a source of error when measuring the reflection from a sound absorber whose reflection coefficient decreased with increasing frequency. That is, the incident pulse contained many harmonics, whereas none were measurable in the reflected pulse. Pass-band filters could not be used for harmonic elimination with the pulse method of testing. Transducers which had reasonably flat response characteristics had to be chosen for the absorption-measuring program.

Appendix 2

FABRICATION OF INSULKRETE*

1. Material

The sawdust is obtained from rough-cut southern pine and sifted through a 1/4-inch-mesh screen to remove wood slabs and pieces of bark. Redwood or cypress is not recommended, as the finished test sample is structurally weak.

The binder is ordinary Portland cement, as used by the building trades. It may be of the slow- or fast-setting type.

The water is used sparingly, making a damp rather than a wet mixture. Water is mentioned under material because of its importance.

2. Preparation

The sawdust is dampened overnight. It is not soaked. If water is added to the sawdust in a container, allow it to drain from the bottom of the container after wetting.

Four parts by volume of loose sawdust are mixed thoroughly with one part of cement, adding just enough water to keep the mixture damp.

To test for proper moisture content, a handful when squeezed hard should just barely hold together and appear damp but not wet.

The mixture is placed in forms and tamped until compressed to about one-half of its original volume. This may be done by motor-driven (air or electric) tampers, or a hand tamper.

A fast-setting cement permits use of the structure within 24 to 48 hours.

*Blocks of this material used by the USRL have been manufactured to USRL specifications by Finrock Industries, Inc., 1184 Spur St., Orlando, Fla. The usual structural material supplied by this manufacturer to the building trades is called "Insulcrete". "Insulcrete" is also listed in the *Thomas Directory* as a trade name used by the Quigley Co. of New York City for an insulating refractory concrete.

Since the material used by the USRL does not correspond exactly to the products known to the trade as "Insulcrete", the spelling of the name has been changed to "Insulkrete" in this report, although the spelling "Insulcrete" has already been widely used by the USRL in discussing tank linings in papers presented before the Acoustical Society of America, in USRL Monthly and Quarterly Reports, and in correspondence.

The material described and discussed in this report under the name "Insulkrete" is identical to the sound absorber formerly called "Insulcrete" by the USRL.

3 Preparation for Test or Use

The sample is immersed in a water-filled container and a vacuum applied to the surface of the water for at least a two-hour period to remove the air bubbles from the concrete. A return to atmospheric pressure forces the water into the voids.

At the USRL, a vacuum is applied at least overnight and sometimes for an entire weekend. Also, a hydrostatic pressure of 1000 psi is applied upon release of the vacuum. This final application of high hydrostatic pressure is not considered essential for tanks operating at atmospheric pressure.

4 Care of Tank

After Insulcrete-lined tanks have been in service for a period of time, a wax-like crust appears on the surface of the water. It starts as a thin film and increases in thickness daily until the water surface is covered with what appears to be a sheet of ice. This substance seems to float by surface tension--it shows negative buoyancy when wetted. After sufficient settling occurs on the bottom of the tank, it can be siphoned out, although the characteristics of the tank appear to remain unchanged by the deposition. A continuous addition of water to the tank was recommended in the body of this report. The addition of acid to neutralize the highly alkaline solution might also prove feasible in preventing the formation.

REFERENCES

- [1] W. J. Trott and C. L. Darner, "The Measurement of the Acoustic Properties of Sound-Absorbent Panels at High Hydrostatic Pressures"—paper presented at the Thirty-ninth Meeting of the Acoustical Society of America.
- [2] P. M. Morse, *Vibration and Sound* (New York, McGraw-Hill Book Company, 1938)
- [3] B. V. English and C. L. Darner, "Reduction of Reverberation in a Water-filled Test Vessel by Use of a Porous Material"—paper presented at the Thirty-fifth Meeting of the Acoustical Society of America.
- [4] P. Vigoreux, *Ultrasonics* (New York, John Wiley & Sons, Inc., 1951)
- [5] USRL Monthly Report, June 1951
- [6] Weinstein, Marvin S., "Some Design Considerations for High Frequency Anechoic Tanks," *J. Acoust. Soc. Am.* **25**, 101. (1953)
- [7] C. L. Darner, *A Transducer to Reduce Standing Waves*, USRL Report No. 18, 5 February 1951